STAGE ACOUSTICS IN CONCERT HALLS – EARLY INVESTIGATIONS

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1 INTRODUCTION

In concert halls the preferred conditions for the audience are now quite well understood. However the optimum conditions for the musicians are less clear. There are several reasons for this. The focus has been more on the audience because this is actually where the music is to be appreciated. But for the audience to hear great music, the stage conditions for the musicians are highly relevant since this is the origin of the sound/music. The musician interacts with what he/she hears quite differently from a (passive) listener. The musicians' focus is not just on enjoying the music, but producing it. What the musicians hear is crucial, affecting their ability to interact confidently in the mutual process of music making (Ueno et al[36]). In this interactive process the musicians automatically adapt to their environment, which makes it more difficult to find relations between cause and effect on a stage.

Since the early '70s there has been increasing research activity on stage acoustics. The two main research approaches have been investigations with orchestras playing in real halls and musicians playing in simulated sound fields (anechoic chambers with loudspeakers). The first approach often suffers from lack of controllability of single acoustic elements, while it is difficult with simulated sound fields to create an apparently natural environment for the musicians. Different design recommendations for stage design and parameters for objectively measuring the stage conditions have been proposed (Gade[16], Naylor[15], Halmrast[31]). There seems to be agreement that musicians have one main concern: getting the right balance between hearing one-self (support) and hearing others. In brief, results show that a small reverberant room will lead to lack of hearing one-self, while a large room with few reflections will lead to lack of hearing others. Lack of support often leads to intonation difficulties, while lack of hearing others leads to timing difficulties within the orchestra (Gade[17]). 'Ensemble' has been used to represent the degree to which a musician can hear others, but ensemble can also be interpreted as the balance point between hearing one-self and others. It remains to be answered what measure is actually required to balance these two listening perspectives.

This paper attempts to provide a contemporary overview of research into stage acoustics and to present a few results found so far. This research project is an on-going three year project which aims to discover more about stage acoustics, based on laboratory experiments combined with gathering information from real concert halls, orchestral musicians and objective measurements.

2 THE STAGE AND ITS SOUND FIELD

Figure 1 below shows a stage and the main elements which have been found to affect the sound field on stage (see 2.1). The side walls, the rear stage wall and ceiling enclosing the stage can be treated as the stage enclosure. The situation shown in Figure 1 is typical for a proscenium stage. In a terraced concert hall, the stage enclosure will be more integrated with the hall space. The stage floor, the presence of the orchestra and eventually risers are common for all stages.

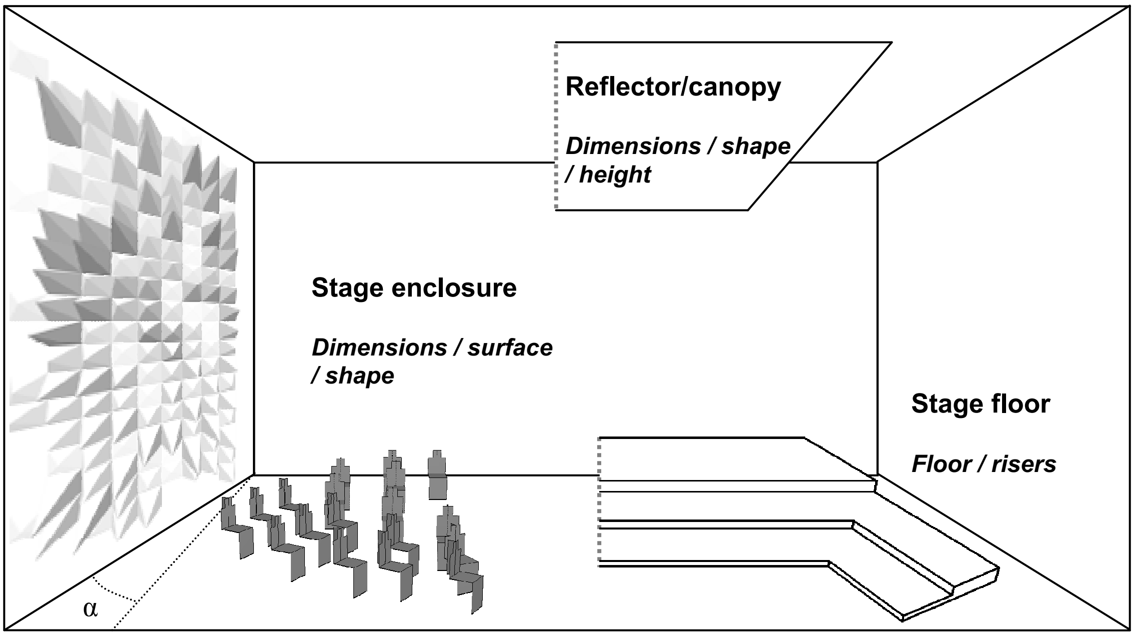

Figure 1: Elements of a concert hall stage. (Splay angle is represented as α^o)

The main objective method for investigating acoustic behaviour in halls is through impulse response measurements. Figure 2 shows a stage impulse response measured in a 1:25 scale model with source and receiver 7.5 m apart, between strings and woodwind with no orchestra present.

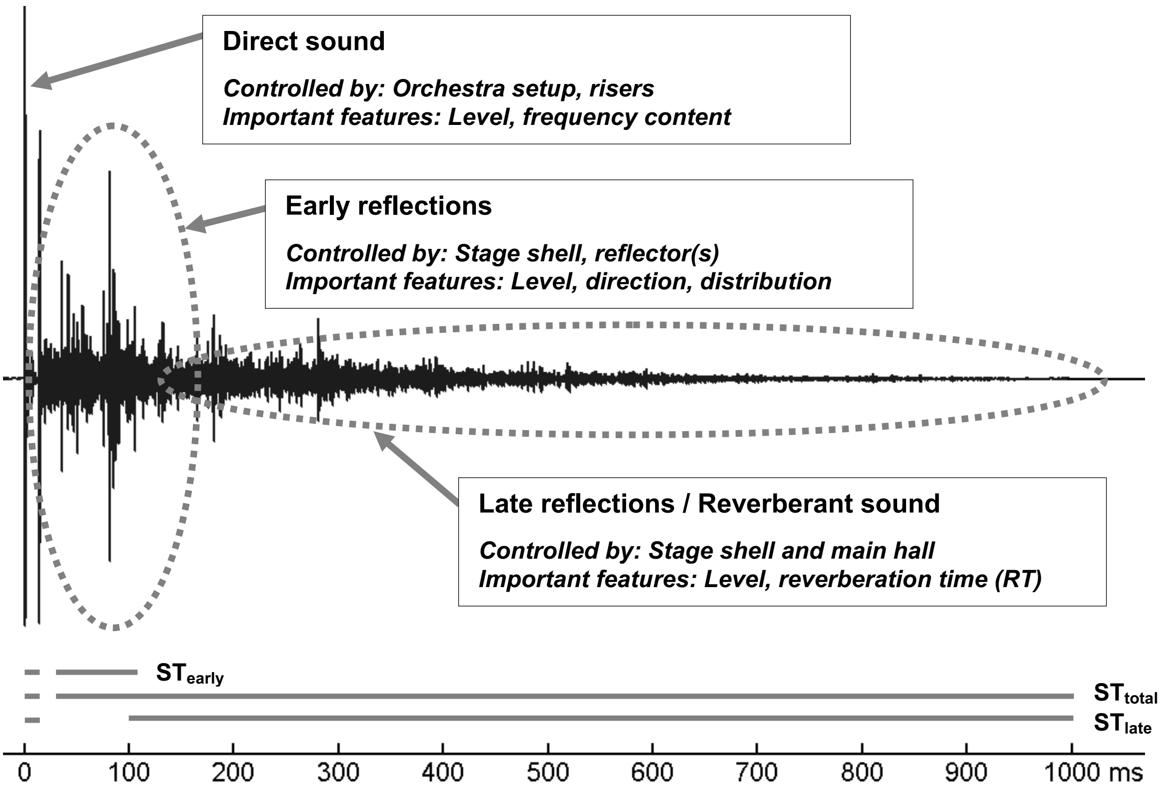

Figure 2: Impulse response on stage with ST integration time intervals indicated. (Linear pressure versus milliseconds)

The three main parts of the impulse response: the direct sound, early reflections and late reflections (reverberant sound), are indicated in Figure 2 above. Also indicated are the elements of the stage that are relevant for controlling these three parts and what have been found as relevant features of them. At the bottom the integration time intervals for Gade's ST parameters (see section 2.2) are also shown.

2.1 Findings in stage acoustics

As mentioned the acoustic conditions on stage can be seen as a result of stage design or which reflections are useful for the musicians (though of course these two perspectives are strongly related to each other). Table 1 below shows findings related to stage design (first part) and sound field (last part).

Attribute	Findings
Stage enclosure	- Need heavy reflecting & diffusing surfaces on the side, rear walls and if possible ceiling (Shankland[3]) - Should be double amount of overhead reflections back to strings compared to woodw. (Meyer and 'Serra[4]) - Reflecting elements at back wall and ceiling maintain directional cues from the hall (Nakayama[12]) - Level of support is controlled by the stage volume (Gade[18]) - Preference for scattered reflections from side and back walls (D'Antonio[21] and Jaffe[24]) - Min. volume 1000 m^3, scattering surfaces on orch. shell, max 16º splay side walls if flat (Kan et al[29]) - Adding orchestra shells could increase ST_{early} on stage by up to 5 dB (Bradley[30]) - Rectangular hall most, fan shaped least favored by musicians (Sanders[33]) - Trumpeters liked front stage pos. without side reflectors, strings disliked this config. (Chiang et al[34]) - Early energy enhanced by reducing splay angle of side walls (Chiang and Shu[35]) - Preference for an absorptive back wall (Kahle & Katz[38]) - A reflector behind the choir improves balance and ensemble with orchestra (Marshall[23])
Reflector / canopy	- Preferred height 7 – 10 m (Barron[1] and Jaffe[24]), 6-8m if possible (Gade) - Should consist of many small reflectors instead of one large (Rindel[19] and Dalenbäck et al[26]) - A low reflector above the strings can affect the balance heard by the audience (Meyer[27])
Floor / Risers	- Risers can make the brass and percussion too loud for the audience (Miller[14])
Direct sound	- High level of direct sound strongly preferred (Krokstad et al[5]) - Delay within the orch. should not exceed 20 ms and high frequency components important (Gade[16]) - Important to have strong direct sound within the orchestra (O'Keefe[28])
Early energy	- The sound field characteristic of greatest importance is the spectrum of early sound (Shankland[3]) - Reflections arriving 10 – 40 ms improve ensemble (Marshall et al[2]) - Reflections beyond 35 ms can contribute to ensemble at lower frequencies (Meyer and 'Serra[4]) - Reflections before 35 ms preferred, if weak direct sound or fast movement & long RT (Krokstad et al[5]) - 0.5 – 2 kHz sound important for ensemble, below 500 Hz may be detrimental (Marshall and Meyer[9]) - Too much early energy on stage can cause the orchestra to sound too quiet in the audience (Meyer[13]) - Early reflections are the main factor for achieving support (Gade[16,17]) - At least 2 or 3 early reflections should arrive before 30 ms (Benade[10,11]) - Reflections beyond 100 – 200 ms are detrimental for the orchestra (Benade[10,11]) - Early reflections are important for ensemble and support (Ueno et al[36]) - Level of other instruments supported by 15 – 35 ms reflections (Meyer[22]) - Strong early reflections at 5 – 20 ms can cause unfavorable coloration effects (Halmrast[31]) - Singers disliked a 40 ms delayed reflection (Marshall and Meyer[9] and Burd and Haslam[25]) - For fast tempo solo singing a 17 ms delayed single reflection is preferred (Noson et al[32])
Late energy / reverberation	- Reverberation is not important for ensemble, but preferable among soloists (Marshall[2], Gade[16]) - Late sound important for musician to 'hear the sound in the hall' (Nakayama[12]) - Choir has a strong preference for reverberant sound (Burd and Haslam[25]) - Shoe-box shaped stage will have the largest build-up of late sound (O'Keefe[28]) - The brass players and the pianist were generally positive about late reflections (Chiang et al[34])

Table 1: Factors appearing to be important related to stage acoustics and findings related to them.

Note: Some of the results listed in Table 1 are for chamber music.

In brief the findings may be summarized as follows: direct sound within the orchestra is important and is influenced by layout and risers. Brass and percussion are the strongest instruments, while strings are normally most demanding on acoustics for their own support. Distributed early reflections are important. Arrivals between early and late reflections (about 100 – 200 ms) can be detrimental. The most important frequencies are 0.5 – 2 kHz, but lower frequencies can play an important role for intonation. For soloists more reverberation is appreciated.

2.2 Objective stage measures – ST and EEL

Based on questionnaires and interviews among musicians as well as laboratory simulations, Gade proposed objective measures for support and ensemble (Gade[6, 16]). ST (Support) monitors early reflections received 1 metre from the source. This energy is simply related to the emitted sound energy: the direct sound (and floor reflection) at 1 metre from the source. EEL (Early Ensemble Level) measures the presence of the direct sound and early reflections. But this energy is measured with a second microphone positioned somewhere else on stage, for instance at another instrument group position, see Figure 3. This energy sum is also seen in relation to emitted energy from the source (direct sound and floor reflection at 1 metre). For ST, t = 0 ms represents the arrival of the direct sound, while for EEL t = 0 ms represents the time of emission from the source. The motivation for the latter was to include the negative effect of a much delayed direct sound at the receiver position. While the time limits for the summing of early energy can vary for ST, it is fixed to 0 – 80 ms for EEL.

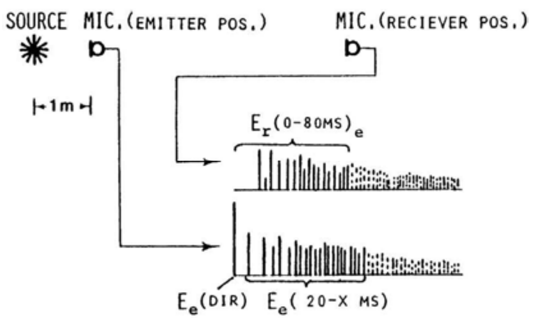

Figure 3: Principles for measuring ST and EEL (Gade[16]).

These parameters are defined as:

$$ST = 10\log\frac{E_e(t_1 - t_2\ \mathrm{ms})}{E_e(\mathrm{DIR})} \qquad EEL = 10\log\frac{E_r(0 - 80\ \mathrm{ms})_e}{E_e(\mathrm{DIR})} \quad \mathrm{dB} \qquad (1, 2)$$

E_e(DIR) is measured over the period 0 to 10 ms. Arithmetical averages are taken for the octave bands 0.25 – 2 kHz for ST and for the octave bands 0.5 – 2 kHz for EEL.

ST is represented in three different forms: ST_{early} where the time interval for the returning sound is 20 – 100 ms (relative to the direct sound), ST_{total} with $t_1 - t_2$ = 20 – 1000 ms and ST_{late} with 100 – 1000 ms. (Previous versions, ST1 and ST2, are not longer being used.) Stage occupancy is important for the measurement. An empty stage will represent the situation for a small ensemble, while chairs and music stands should be included when measuring for the orchestra situation. See Gade[20] and Jeon and Barron[39] for more details on how these parameters should be measured.

Only the ST parameter which only takes the returning early reflections into account (not the direct sound transmission) has been shown to be a successfully correlate with subjective evaluation (Gade[17]). ST was found to correlate well with the judgment of 'support' and quite well with judgments of 'ensemble'. For that reason EEL has not been used much recently.

2.3 How the ST parameter monitors important aspects of stage acoustics

If we compare the nature of the ST measures(s) and what has been found (Table 1), ST_{early} measures the total energy of early reflections present. ST_{early} measures the presence of what have been found to be useful reflections, though there still are disagreements regarding the time limits of useful reflections. ST_{late} can measure the late energy found to be important for solo performance. But there is no discrimination regarding density or direction of the reflections. Potential coloration effects are not measured either. This can explain why there is not always good agreement between the ST_{early} value of a stage and its reputation among musicians playing on it. But since it monitors some of what seem to be important factors, it can often distinguish between the good and the really poor stages. There has been experimentation with other time limits for the summing of early energy, but these alternative versions were found in chamber music halls to correlate highly with ST_{early} values (Chiang et al[34]).

One of the advantages with the ST (and EEL) parameter is that a standardized way of performing measurements on stage is defined. However the measured value is quite sensitive to source directivity (not omni-directional) and, since the microphone is only 1 metre away from the source, deviations in relative transducer position. Figure 4 below shows octave band values of the emitted sound from a dodecahedron when rotated around its axis. The dodecahedron consists of 12 100 mm elements and has a radius of about 330 mm. The measured spectrum is with the microphone 1 m from the centre of the dodecahedron.

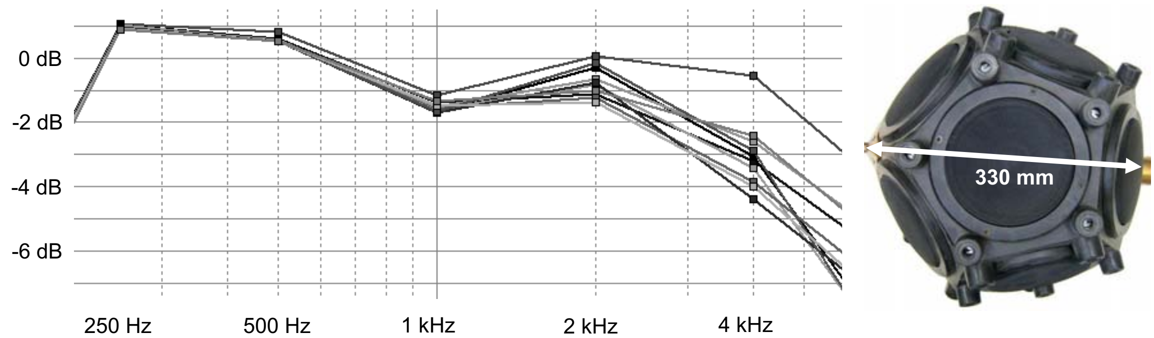

Figure 4: Frequency response of dodecahedron at 1 metre, measured with different rotation angles.

The results show a 2 dB variation in the 2 kHz octave band. A 2 dB change in one octave band can cause typically a 1 dB change of the four octave band average value (0.25 – 2 kHz). If the microphone distance to the loudspeaker varies 50 mm, this will cause a 0.5 dB change in measured direct sound level (including the floor reflection) as well. When averaging between three positions, Gade[20] found the accuracy to be within 0.2 dB. If the 250 Hz octave band is omitted (only averaging from 0.5 – 2 kHz, EEL) or not averaging between several positions/measurements, the influence of source directivity and transducer positions will increase.

2.4 Alternative measures for ensemble

As described above, only ST_{early} (but not EEL) has proved to correlate well with subjective measures of 'support' and 'ensemble'. Gade[17] suggested that this could be caused by averaging measurements done between different orchestra groups without knowing which paths were critical for stage communication. That the time reference (t = 0) is set to the time of sound emission for EEL can be another possible cause. The consequence of using this time reference is that different numbers of early reflections are included with varying source-receiver distance. And the measured direct sound will also vary depending on how the direct sound from real instruments transmits through the orchestra with musicians present.

The direct sound within the orchestra is difficult to simulate with measurement equipment and is also not dependent on the orchestra shell. It is affected by the orchestra configuration, risers and the floor.

An alternative way to measure ensemble or rather ensemble balance (between hearing one-self and the others) could be to measure with a fixed microphone and two source positions. The early sound with the source representing one-self is compared with the early sound from others. See Figure 5 for an illustration of the measurement setup. The direct sound from the source is not included and the source is moved, not the microphone. The ensemble balance (EB) can be defined as follows:

$$EB = 10 \cdot \log\left(\frac{E(20-100\text{ ms})_{one-self}}{E(t-100\text{ ms})_{the\ others}}\right) \quad \text{dB} \qquad (3)$$

This assumes a constant acoustic level for the source between the two separate measurements. For the moment, the optimum start time for integration of sound from others, t, is left undecided; t=0, the time of the direct sound from ‘others’ looks a reasonable choice. The measurement setup will be compatible with ST measurement with all transducers at a height of 1 m above the stage floor.

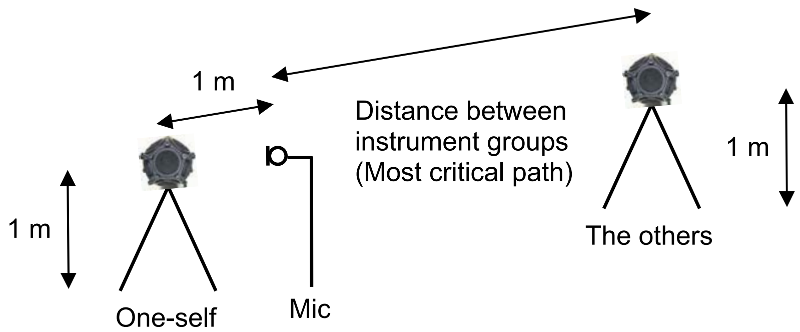

Figure 5. Measurement setup.

Findings indicate that the strings are the most demanding for support and the brass/percussion has the largest potential of getting too loud for the strings. This or any other possible “most critical paths” within the orchestra could be used instead of averaging between many paths. An interesting question with regard to this is to which degree the musicians listen to the others while playing themselves, or during time gaps where they do not play themselves.

By simply summing energy, neither the density nor direction are measured, but what appears to be of most concern for the musicians can be measured. A better approach to investigate the importance of diffusion on stage seems to be employing in-ear microphones at the musicians’ ears while playing on stage, as used by D’Antonio[21].

Halmrast[31] has proposed a method for measuring the comb filtering effect caused by interference between the direct sound and early reflections within the orchestra. This is also done with the musicians present on stage, though this may be difficult in practice in many halls.

3 SCALE MODELLING RESULTS

One of the aims of this research project is to establish the main reflected sound components that come back to the musicians. While it is in principle easy to determine this by computer simulation modelling, we need to be aware of the extent to which diffraction influences reflection level. The following study is based on scale modelling measurements of simple reflection from finite surfaces.

3.1 Theory of reflection from suspended finite surfaces

Based on earlier work by Cremer[41], Rindel[40] has published a simple theory that enables calculation of the diffraction effect for reflections from free-standing finite surfaces. In this discussion, we shall consider only situations where one dimension of the reflector is large, so that diffraction effects are determined by the other (finite) dimension only. Rindel presents results for the diffraction effect on its own (10logK) for the geometrical sound path; this diffraction effect is added to the reflection level based on normal spherical propagation. Figure 6 shows the predicted result for 10logK, x is a normalized measure of frequency. The figure shows the predicted situation for a reflection off the centre and edge of the reflector.

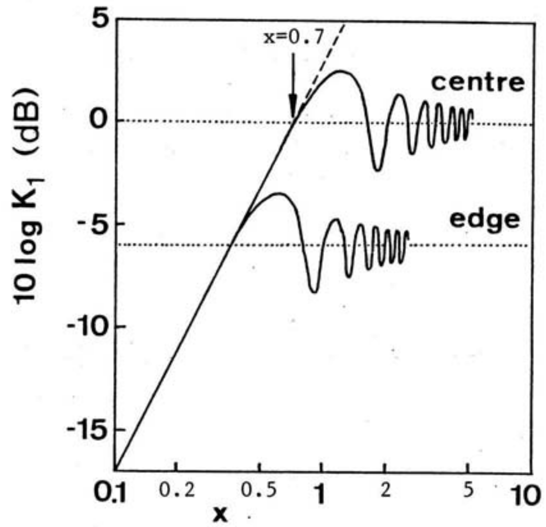

Figure 6. Influence of diffraction on reflected level along the geometrical path (after Rindel[40]). x is normalized frequency.

Figure 7 shows the basic geometry of reflection; reflector height B is considered infinite for this discussion. The response in Figure 6 is simplified as in Figure 8. Much of the discussion considers the value of the limiting frequency f_0 Hz. At frequencies above f_0 , there is 'no' diffraction effect; below f_0 the diffraction effect ΔL (= 10.logK) increases 3 dB per octave for decreasing frequency. The following equations are based on Rindels'[40] (c is the speed of sound):

$$f_0 = \frac{c}{\left(\frac{1}{s}+\frac{1}{r}\right).A^2\cos^2\theta} \quad or \quad f_0 = \frac{c.s}{2A^2\cos^2\theta} \quad when\ s = r \qquad (4)$$

$$\Delta L = 10.\log\left(\frac{f}{f_0}\right)\ dB \quad for\ f < f_0 \quad and \quad \Delta L = 0dB \quad for\ f > f_0 \qquad (5)$$

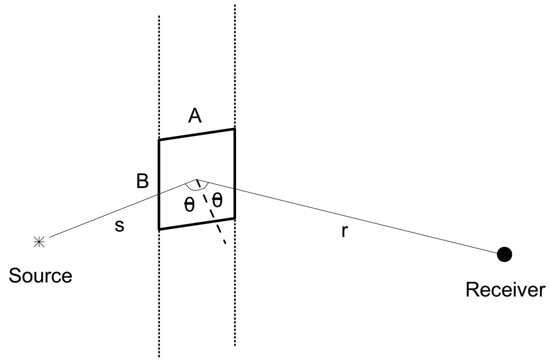

Figure 7. Basic geometry of reflection off a finite plane surface A x B. s and r are distances from the source and receiver to the reflector. In this discussion, B is taken as infinite.

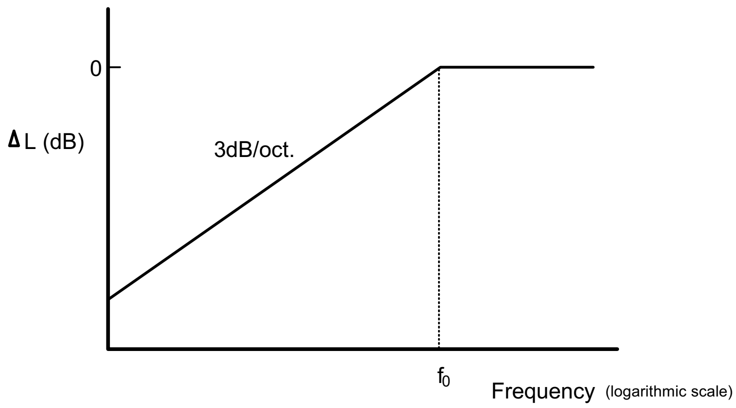

Figure 8. Simplified diffraction effect for reflection off a strip reflector with a finite width.

The simple rule-of-thumb regarding diffraction that was used 30 or more years ago stipulated that above the wavelength of sound equal to a relevant dimension of the reflector, one could expect diffraction effects. According to equations (4), this approach is clearly inaccurate, since, as well as the reflector dimension, A, the source and receiver distances are also involved. Note that doubling the width of the reflector shifts the limiting frequency two octaves lower.

3.2 Reflection from a freely suspended finite surface

Measurements of reflection amplitude for reflection off a finite sized strip at normal incidence were made at a scale of 1:25. The reflection was temporally gated and results normalized to the reflection amplitude from an infinite surface along the geometrical reflection path. All dimensions and frequencies quoted here have been converted to full-size.

Figure 9 shows the measured reflection level, relative to the predicted value for geometrical reflection from an infinite surface at 0° reflection angle. Reflection level measurements were made at 10° intervals. The predicted behaviour for light reflection from a mirror would be 0 dB level over the 31° segment shown in Figure 9 by the thick grey lines, with no reflection outside the segment (i.e. -∞ dB). This characteristic is assumed by computer simulation models which ignore diffraction.

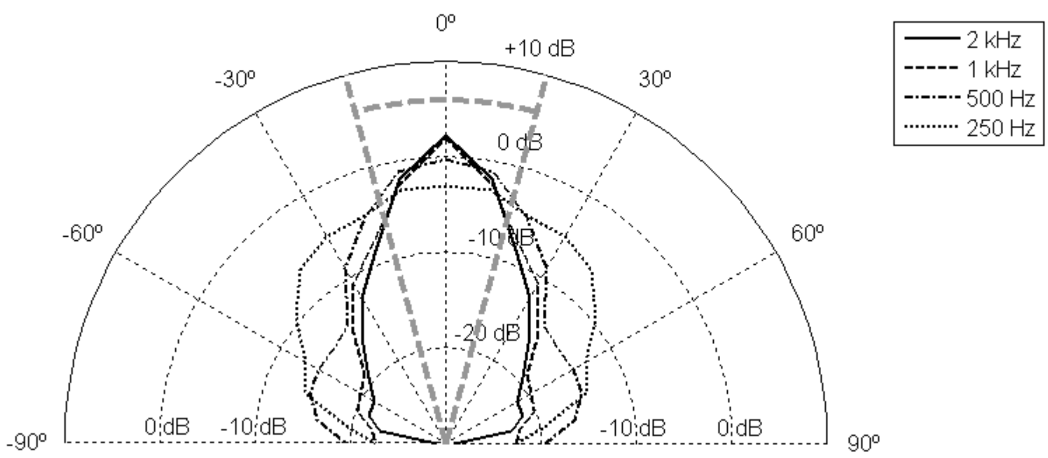

Figure 9. Polar plot of reflection amplitude for normal incidence off a 1 m wide panel as a function of reflection direction. 0 dB represents the reflection amplitude from an infinitely wide surface along the geometrical path. Source and receiver distances are 5 and 3 m respectively. The grey radial lines indicate the region of geometrical reflection. Plots are for octave bands with centre frequencies of 250 – 2000 Hz.

It is interesting to compare the measured reflection levels in Figure 9 in the region around 0° reflection angle with the predictions in Figure 6. The value of f_0 for the relevant distances is 640 Hz. At 0° reflection angle, the finite reflector provides a small amplification at 1 and 2 kHz compared with an infinite reflector. In Figure 6 we find that for parameter values above x = 0.7 (equivalent to frequency greater than f_0), there are peaks (and dips) which correspond to this behaviour. At the 250 Hz octave (frequency less than f_0) the measured diffraction effect for the 0° reflection is negative as predicted in Figures 6 and 8. 640 Hz (f_0) is within the 500 Hz octave and the measured result is again close to predictions in Figure 6.

The measured reflection level at ±15.5°, the limit of the geometrical reflection in Figure 9, is about -4 to -6 dB, which careful examination of Figure 6 shows as compatible with predictions for the edge reflection condition0

Beyond ±15.5° reflection angle, the limit of the geometrical reflection, Figure 9 indicates that there is significant energy diffracted into the shadow zone. This scattering may be significant for reflections back to musicians on stage. The magnitude of the scattering is greater for shorter source and receiver distances. Note that the Rindel's theory in Figure 6 and equations (4) refer to a freely suspended panel; whereas when a reflecting panel is joined to another at a different orientation the diffraction will be different. Reflection off finite panels is discussed in detail in Cox and D'Antonio[42].

3.3 Reflection from a cornice associated with a balcony soffit

A feature commonly found in classical rectangular halls is horizontal balconies which run along the side walls. A recent example with this feature is to be found in Birmingham Symphony Hall in England, which opened in 1991. Next to the stage, the balcony soffit will provide a cornice reflection (sometimes called a cue-ball reflection) back to the stage. As is well know, the reflection direction for reflections off a 90° cornice runs parallel to the incident sound.

The situation for this case is shown on the left-hand side of Figure 10. In reality the musician is both source and receiver and the incident and reflected 'rays' are superimposed. Model measurements were made for this condition with a 1 m and 2 m wide balcony shelf. It can be assumed that the vertical wall below the balcony is of infinite height.

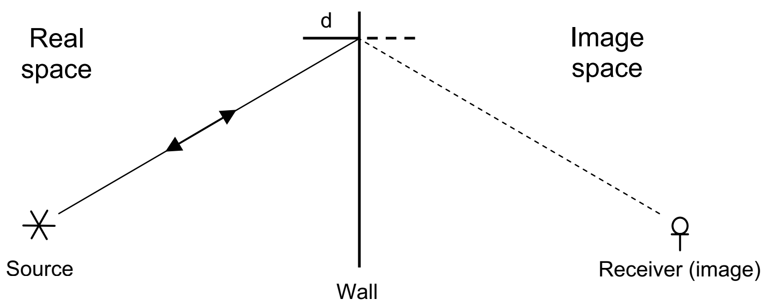

Figure 10. Illustration using image space showing how reflection from a cornice (balcony shelf and wall) is equivalent to reflection from a double width horizontal panel.

The measured reflection level for the cornice reflection for both widths of balcony (d) of 1 and 2 m is given in Figure 11. Again 0 dB corresponds to the value for reflection off infinite surfaces. Figure 11 shows that agreement between measured and predicted in Figures 6 and 8 for both values of d is good, except for one detail, which is the predicted values for f_0 in each case. Note that the values of the 'corner' frequencies (f_0) for d= 1 and 2 m are two octaves apart as predicted by equations (4).

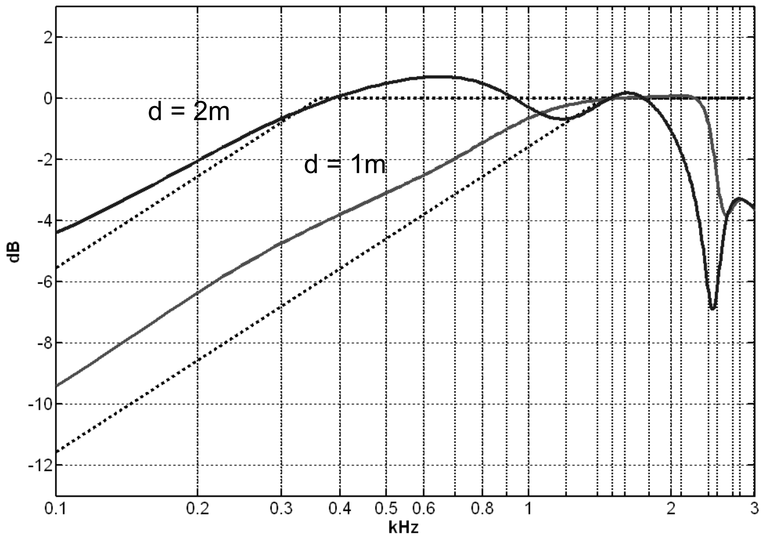

Figure 11. Reflection level as a function of frequency for a reflection off cornices with horizontal dimensions of d = 1 and 2 m. The 0 dB level is the predicted value for d as infinite. Dotted lines indicate expected responses according to equations (5), but for reflector widths of 2xd.

The predicted value of f_0 for d = 2 m is 1434 Hz, whereas the 'measured' value is two octaves lower at 358 Hz. This suggests that the effective width of this balcony is 4 not 2 m. The same situation occurs for the 1m wide balcony, which behaves as if it was 2m wide. A likely explanation for this behaviour is shown in Figure 10. On the right-hand side of the wall, an image space has been illustrated. The width of the balcony is also found in the image space, so that the cornice reflection can be represented as equivalent to a simple reflection off a horizontal panel of width 2d.

This result indicates that the strength of reflection from a balcony cornice at low frequencies is 6 dB greater than might at first be guessed. In other words, reflections back to musicians from narrow side wall balcony soffits are potentially more valuable than expected.

4 CONCLUSIONS

While the physical conditions on stage are in principle easy to study, the situation for the players is clearly complex. Though there are now many papers on stage acoustics, several mysteries remain. Not least is the problem of how far and in what manner musicians adapt to new performing environments. An obvious starting point for this study is to examine Gade's proposed measures for support and ensemble on stage, ST_{early} and EEL.

There appears to be reasonable evidence that the Support measure ST_{early} relates well to the acoustic support which individual musicians receive. There is still some uncertainty about the relative importance of early and late energy reflected back to the musician. ST_{early} also takes no account of source directivity and reflection direction, which must be important for many instruments and players.

The measure for ensemble proposed by Gade, EEL, is less well substantiated by subjective evidence. A possible alternative measure to EEL is proposed here.

Section 3 above investigated the possible significance of diffraction for reflections in the stage area. In both cases, simple geometric modelling may be inaccurate.

5 ACKNOWLEDGEMENT

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